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Non-traditional Machining Techniques for Fabricating Metal Aerospace Filters

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Abstract

Thanks to recent advances in manufacturing technology, aerospace system designers have many more options to fabricate high-quality, low-weight, high-capacity, cost-effective filters. Aside from traditional methods such as stamping, drilling and milling, many new approaches have been widely used in filter-manufacturing practices on account of their increased processing abilities. However, the restrictions on costs, the need for studying under stricter conditions such as in aggressive fluids, the complicity in design, the workability of materials, and others have made it difficult to choose a satisfactory method from the newly developed processes, such as, photochemical machining (PCM), photo electroforming (PEF) and laser beam machining (LBM) to produce small, inexpensive, lightweight aerospace filters. This article appraises the technical and economical viability of PCM, PEF, and LBM to help engineers choose the fittest approach to turn out aerospace filters.

Keywords: aerospace filter; photochemical machining; photo electroforming; laser beam machining

1 Introduction

One of the main reasons for using non-traditional fabrication methods to fabricate filters, in comparison with other methods such as stamping, drilling and milling, is their capability to produce micro holes economically and efficiently[1]. However, the correct choice of photochemical machining (PCM), photo electroforming (PEF) or laser beam machining (LBM) is still difficult because of the technical and cost limitations[2], imposed by: complexity of design, process ability, surface quality, precision required, cost-effectiveness of rival processes.

Moreover, the contamination capacity is a strong function of the total filter surface area and initial porosity, which is also heavily dependent on the fabrication methods[3].

In an attempt to evaluate non-traditional fabrication methods that are now being used in this specific field, three kinds of commercial metal aerospace filters are described, to demonstrate a choice of suitable manufacturing techniques[4-5]. A flow-diagram is provided, which will aid the selection process for manufacturing aerospace filters with minimal cost.

2 Aerospace Filtration and Filters

2.1 Aerospace filtration

Aerospace filtration is generally classified as either surface or depth filtration, depending on where the particle retention takes place.

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Surface filtration is accomplished by the impingement and retention of particles on a single surface plane, namely, the outer surface of the filter element. Filters that block contaminants on only one surface, tend to inhibit the release of trapped contaminants and lend themselves to cleaning by back-flushing to a fully clean condition[7].

Conversely, depth filtration is the retention of contaminant particles throughout the thickness of the media. Consequently, it is possible that given enough time, some of the contaminants may migrate all the way through the media.

Generally speaking, the efficiency and cost-effectiveness are the main problems of filtration. The finer the filter, the more readily it becomes clogged in the presence of coarser contaminants.

2.2 Aerospace filters

The propulsion, transmission and environment systems are the main units in an aircraft. Hence aerospace filter assemblies for fuel, lubrication and hydraulic systems, oil scavenger filters, electronic equipment cooling filters, cabin air recirculation filters and even space shuttle environmental system filters are manufactured to demanding performance and reliability standards[8-12].

Contamination levels in these cases are low for obvious reasons, as shown in Table 1. These standards are commonly used in the UK, and give a wide range of particle size distributions for different aerospace applications. Other standards such as DEF STAN 05-42, NAS 1638, and ISO 4406 are also in common use throughout the world[13-15].

Table 1 Cleanliness standards for fuels contamination level classes for hydraulic systems in aerospace[6]

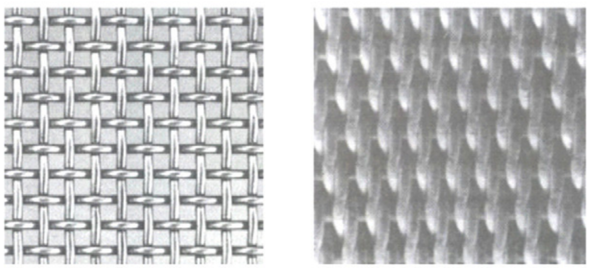
	Satellite			Missile			Sub-miniature servo-valves, some aircraft oils as new		
	Particles per 100 mL by dirt contamination								
Size range /μm	Class 1-H			Class 2-H			Class 3-H		
	Class (red)	'Tol' (green)	Distribution/%	Class (red)	'Tol' (green)	Distribution/%	Class (red)	'Tol' (green)	Distribution/%
+100	7	2	0.015	7	2	0.001 5	7	2	0.000 7
50-100	15	4	0.044	15	4	0.003 0	15	5	0.001 6
25-50	94	27	0.279	104	29	0.023 0	133	40	0.014 0
15-25	290	64	0.836	370	71	0.083 0	529	160	0.057 0
10-15	701	180	2.086	1 810	518	0.406 0	3 677	1 128	0.401 0
5-10	1 617	415	4.812	22 320	6 377	5.019 0	50 050	15 617	5.473 0
1-5	30 882	7 918	91.899	420 000	120 000	94.461 0	860 606	260 780	94.053 0
Cum. total	33 606	8 610	/	444 626	127 001	/	915 017	277 282	/

Unfortunately, not all filtration in aerospace applications can afford the cost and weight required by normal filters. New filtration problems continue to arise, such as the long-term operating life in aggressive fluids, which necessitate the employment of advanced manufacturing techniques.

3 Manufacturing Techniques

3.1 Traditional fabrication methods for metal filters

The techniques for manufacturing metal filters vary according to the composition of the filter materials. Woven wire cloth is often used for filtration. It can be woven from nearly any metal ductile enough to be drawn into wire form. The preferred materials are phosphor bronze, stainless steel and Monel, as shown in Fig.1.



(a) Plain dense weave (b) Twilled Dutch weave

Fig.1 Woven wire cloths.

Mesh filter discs made of stainless steel woven wire mesh are made rigid by sintering, a process which produces fusion bonds at all contact points.

Sintering maintains the uniformity of the original weave and fixes the size and shape of the mesh.

Perforated metal plates are more rigid and can be made stronger than woven wire cloth and so find particular application in strainers, coarse filters and screens. Fabrication methods include punching/ stamping, drilling and milling.

3.2 Non-traditional fabrication methods

Unlike the machine shop methods such as stamping, drilling and milling, many non-traditional perforation methods leave the material free of induced stress or deformation. Applications range from heavy gauge effluent filtration to extremely fine thin-gauge filters for liquids and gases. In many cases, fabricated metal meshes provide better value and performance than woven wire.

PCM, a chemical machining process, as shown in Fig.2, is used to produce components for many types of aerospace applications.

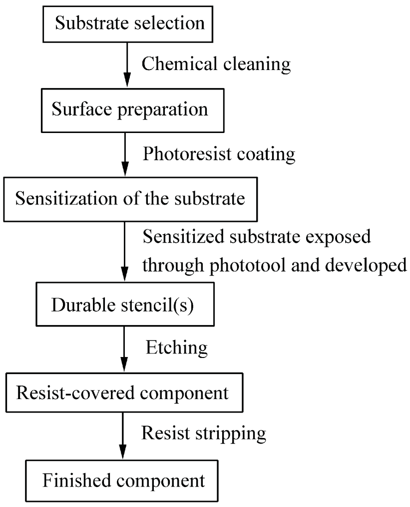


Fig.2 PCM process.

Conventional PCM would usually be an ideal technique to make some of the required often complex planar shaped components. However, the combination of an accelerated corrosion process and a corrosion resistant material such as titanium produces the following problems[16]:

Aggressive etchants such as HF and HNO_3 are required in place of the more innocuous conventional etchants.

More aggressive etchants and/or the use of higher etching temperatures necessitate the use of more durable photo resists.

PCM is a cost-effective fabrication method, whereas, PEF may be the only viable process capable of achieving very high resolution.

PEF (as shown in Fig.3) involves electroplating of metals onto an electrically conductive mandrel which is patterned over its surface with an insulating resist stencil. The PEF component is then removed from the mandrel after plating to the required thickness. One of the limitations of PEF is the restricted range of metals (usually nickel, copper, some of their alloys, silver and gold) available[17-18].

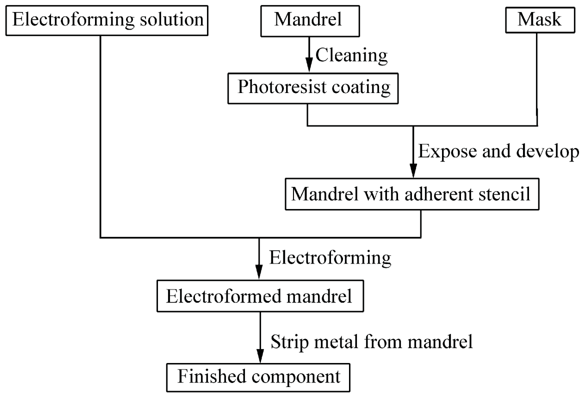


Fig.3 PEF process.

The laser today is a useful processing tool for many applications. Typically, the laser is useful for removing not only cylindrical sections, but also conical and rectangular sections. Laser-perforated metal plates have been selected for filter elements in some aerospace applications. The cost of operating a pulse laser system can be very low when the volume of material to be removed is small. It is a precision process that utilizes high energy laser light pulses to provide both accurate apertures and positional tolerances. This process can be enhanced by combining it with PCM or PEF technologies to provide hybrid solutions such as multi-level filters[19].

3.3 Comparison of fabrication methods

Generally speaking, the primary principles of these methods vary from one another in the physical and chemical process. There are many advantages and disadvantages associated with each method. To define the technical differences in the fabrication methods, traditional and non-traditional methods have been compared in detail, as shown in Table 2.

However, to all designers, the chief concerns are the materials processing ability, surface quality, accuracy and cost-effectiveness of rival processes, which means that not only the technological, but also the economic factors are definitely important. For instance, PCM is a multi-stage process requiring consumables such as cleaners, photo resists, etchant, and strippers to be included in the cost which is therefore relatively high. Although photo tooling involves lower costs than preparing a punch and die, it is easy to understand that PCM is cheaper for low volume production, whereas, stamping is cheaper for high volume production.

Table 2 Technical comparison of fabrication methods

	Minimum aperture size (D: Depth)	Maximum material thickness (T: Thickness)	Material	Process advantages	Process disadvantages
Stamping	0.50T(low carbon steel) 0.75T(high carbon steel)	13 mm	Nonbrittle metals	①Forming operations can be carried out whilst blanking ②Fast	①Long lead times ②Deburring required
Drilling	0.2T (Normally)	Depends on drill size	Nonbrittle metals	①Variable edge profile ②Fast	①Deburring required ②Drill fragility ③Skilled operatives required
Milling	0.1T (Normally)	10 mm	Nonbrittle metals	①Thin slots ②Relatively high aspect ratio	①Deburring required ②Mill fragility ③Tool wear
PCM	1.1T (most metals)	1.5 mm (6 mm for very low resolution)	All metals (but vary in etchability)	①Burr-free & stress-free ②Characteristics of metal material not altered ③Variable edge profile	①Multi-stage process ②Thickness limitation
PEF	0.1T-0.5T	2 mm	Usually nickel, copper, silver or gold	①Very high resolution ②Parts can be produced with unique multi-level features	①Multi-stage process ②Restricted range of metals ③Slow
LBM	0.02T	10 mm	Almost all metals (except aluminum, brass, etc.)	①High aspect ratio ②High precision ③High efficiency	①Heat affected zone ②High facility cost

4 Aerospace Filters Manufactured by Non-traditional Fabrication Methods

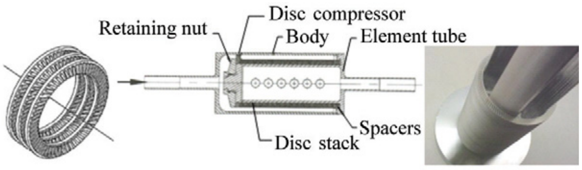
4.1 Advanced fluid filters

Etched disc filters, in stainless steel or titanium, have been used as fluid filters in aerospace applications for a long time because they offer a number of advantages over other filtering media such as wire mesh or sintered materials[20].

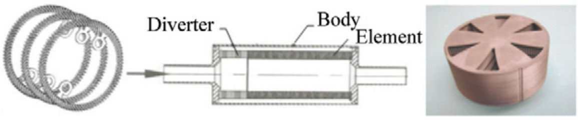
To accomplish the disc design economically, the discs are photochemically machined using a negative working photo resist as the basic design tool to differentiate between the areas to be etched and the areas not to be etched. This etching process is tightly controlled, using statistical process control methods to ensure the geometric accuracy necessary to meet the performance requirements. The fabrication process is completed by stacking the individual chemically etched discs, to make up the filter element assembly.

Recent advances in etched disc filtration technology combine two distinct design and manufacturing features. The new design concept has produced a filter with a more efficient pressure drop and dirt capacity holding characteristics. Additionally, the new process of diffusion bonding has minimized the manual assembly of the filters with substantial improvement in the efficiency and productivity of the assembly process.

Fig.4 shows the new, efficient titanium disc configuration. The physical size in terms of I.D. (Ø31.29 mm) and O.D. (Ø36.83 mm) is reduced for the same flow area as the traditional etched disc design. These high efficiency discs are approximately 25 μm thick (compared with 50 to 80 μm thick in the case of traditional discs). Therefore, more discs can be stacked per mm of filter length (approx. 40 pcs). In fact, the open area in this new, high efficiency, etched disc design is about 50%, as compared to only 15%-20% in the traditional design[21].



(a) Traditional etched disc and filter assembly



(b) High efficiency etched disc and filter assembly

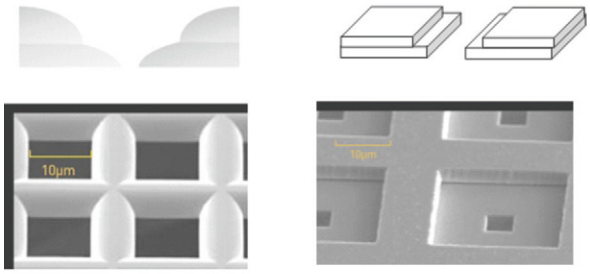
Fig.4 Titanium disc filter and etched disc. (Courtesy of Vacco Industries, CA, USA) [22]

Therefore, both of these new features serve to reduce the total weight and volume envelope required for a specific design parameter. Traditionally, filters with similar flow/pressure drop requirements weighed approximately 990 g; the high efficiency filter weighs only 86 g. This research and development study has therefore resulted in a new generation of optimized etched disc filters for space applications[22].

4.2 Ultra fine micro filters

PEF is a combination of photo resist imaging and electroforming. Material thickness can be as thin as 3-4 μm. Dimension tolerances are generally ±10 μm or better. Positional tolerances are normally ±(1-2) μm and through holes are as small as 2-3 μm. Parts can be produced with unique multi-level features, as shown in Fig.5.

If a design can be drawn in a 2D CAD file, the chances are good that it can be electroformed. Therefore, parts and components are produced for many markets, including masking, sieving, avionics, filtration, medical devices, electronics, scientific controls and much more[23].



(a) Overgrown (b) Multi-level

Fig.5 Unique structures in nickel mesh. (Courtesy of Tecan Ltd., Weymouth, UK)

Recently, LIGA or LIGA-like technology has been introduced to the micro fabrication area, especially for non-silicon materials[24]. The high aspect ratio of microstructures can be realized with a high resolution photo resist (e.g. SU-8) for micron or sub-micron features, which can be used to fabricate micro filters for power and propulsion systems in aerospace applications, such as, micro air vehicles (MAVs) and future satellites.

4.3 Titanium propellant filters

The long-term operating life of a propellant filter in aggressive fluids is a key constraint in the design of this product, as only a few materials are compatible with such fluids over long periods. The use of titanium in contact with these fluids, typically mono methyl hydrazine (MMH) and nitrogen tetroxide (NTO), is a long-term, flight-validated solution selected for the development of the propellant filter in Europe[5].

However, because of the poor ductility characteristics of titanium and irregularity in diameter of the wire, titanium screen mesh and coiled wire technologies are not suitable for this application.

It is possible to manufacture a filtering medium using a titanium plate. The filtering characteristics are provided by the definition of the perforations. Absolute filtration rate is directly linked to the dimensions of the holes. Other characteristics (pressure drop and dirt holding capacity) depend on the global transparency (ratio between the open area and the total area of the perforated plates). It is necessary for this application to use a high accuracy process such as LBM.

The feasibility of this technology in terms of perforating had been previously validated by Sofrance. The laser technology produced results in performance compatible with the specifications, given the filtering level required as 20 μm, with a sufficient uniformity in the dimensions of ±2 μm. The shape of the perforations and the filtering unit are shown in Fig.6.

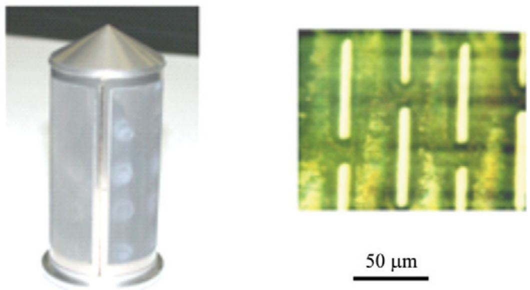


Fig.6 Titanium propellant filter element and micro features. (Courtesy of Sofrance, Nexon, France) [5]

5 Summary

With the advancement in manufacturing more reliable, lightweight, high-capacity and cost-effective filters, aerospace system designers have new options for utilizing these superior technologies. However, the choice of the manufacturing method of metal aerospace filters is not always easy to determine. This article has introduced three kinds of non-traditional fabrication methods to demonstrate how to meet the demands of special aerospace filtration requirements.

Fig.7 explains the primary principles and procedures of the choices, which mainly depend on technological and economic factors. As a consequence, process choice will be based on a trade-off between cost and performance aspects only. Conventional PCM would usually be an ideal, economic technique to make some of the required, often complex planar components. Electrolytic photo etching (EPE) and sonochemical photo etching (SPE) are also being introduced into this area, which would enable the use of safer etchants to facilitate the etching process.

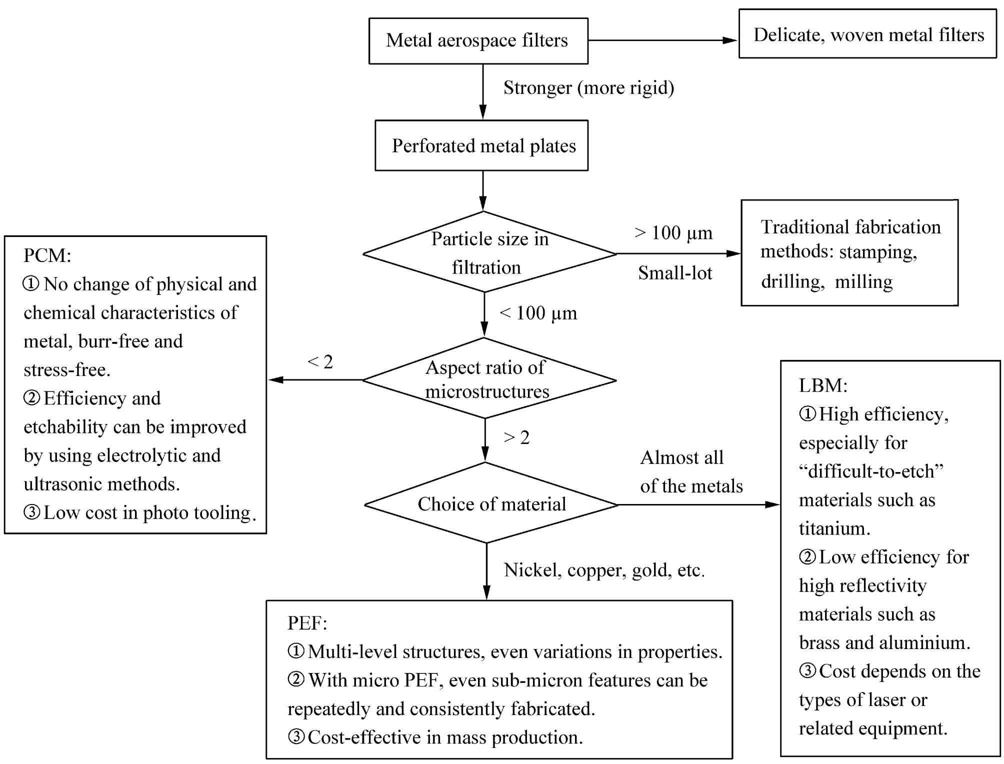


Fig.7 Flow-diagram of choice of manufacturing techniques.

PEF may be the only viable process capable of achieving a very high resolution. It is an electro deposition process, so there is no formation of burrs, HAZ or other edge defects. Typical profiles can be overgrown and stepped multi-level, as seen in Fig.5. One of the limitations of PEF is the restricted range of metals.

LBM is a direct CAD-to-production process with no photo tooling required. This enables a rapid turnaround, with delivery of certain products on the same day. Laser-perforated metal plate is the selected technology for filter elements in aerospace applications. It is a precision process that utilizes high energy laser light pulses to provide both accurate apertures and positional tolerances.

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Biography:

Wang Wei Born in 1973, received the Ph.D. degree in mechanical engineering from Nanjing University of Aeronautics and Astronautics in 2000. His main research interests are micro fabrication and non-traditional machining technologies.

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